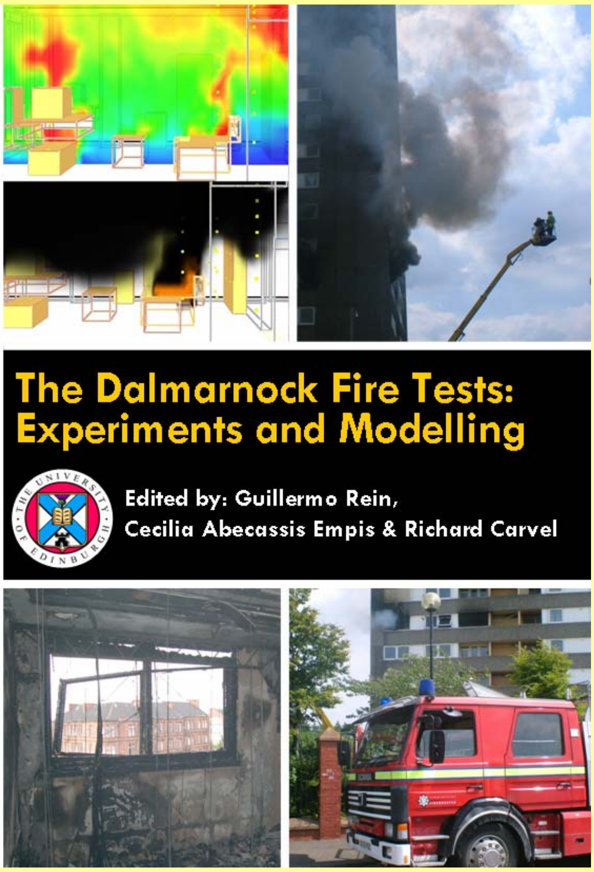
The Dalmarnock Fire Tests: Experiments and Modelling
Edited by G. Rein, C. Abecassis Empis and R. Carvel



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8. Behaviour of the Structure during the Fire

By Martin Gillie and Tim Stratford

Introduction

The conventional method of testing structures for fire resistance has been to subject single structural elements to a Standard Fire Test (BS476, 1987) and thus obtain a fire resistance rating in the form of a time to failure. This approach has been severely criticised in a number of ways, such as those discussed by Drysdale (1998), however, it is still widely used. From a structural engineering point of view, one of the most serious criticisms is that the manner and time to failure of a single structural element in a furnace test bears little relation to the time to failure of a complete structural system. Furnace tests therefore do not provide the information needed to undertake performance-based designs of structures for resisting fire. Over the last ten years a considerable amount of work has been undertaken into understanding the global behaviour of steel and steel-concrete composite structures in fire (e.g. Bailey and Moore, 2000; Elghazouli *et al.,* 2000; Gillie *et al.,* 2001; Huang *et al.,* 2003). This work has included both gathering of experimental data and analysis of that data. As a result, the knowledge and computational tools available are now adequate for performance-based designs of these kinds of structure to be undertaken with confidence (e.g. Arup Fire, 2003).

By contrast, the understanding of the global behaviour of heated concrete structures has received relatively little attention. This is in part due to the lack of experimental data on complete concrete structures in fire and in part due to the difficulties associated with numerical modelling of concrete structures. Fire tests on concrete structures are infrequent. Prior to the Dalmarnock test discussed here, the most complete set of test data available was that produced by a fire test on the reinforced concrete frame at Cardington, UK (Bailey, 2002; Canisius *et al*., 2003). Unfortunately this test suffered from instrumentation failure prior to the end of the test and so the dataset is incomplete. More recently, a number of tests have been conducted on model-scale concrete slabs with the aim of verifying design methods for composite structures in fire (Bailey and Toh, 2006). However, the data available on heated concrete structures until the Dalmarnock tests remained very limited. In order to alleviate this lack of data, the Dalmarnock structure was heavily instrumented prior to Test One. The type of instrumentation installed, the results and their implications are the focus of this chapter. The fact that both the fire and the structure were instrumented means that Dalmarnock Test One was the first structural test on a heated concrete structure in which all of the following applied:

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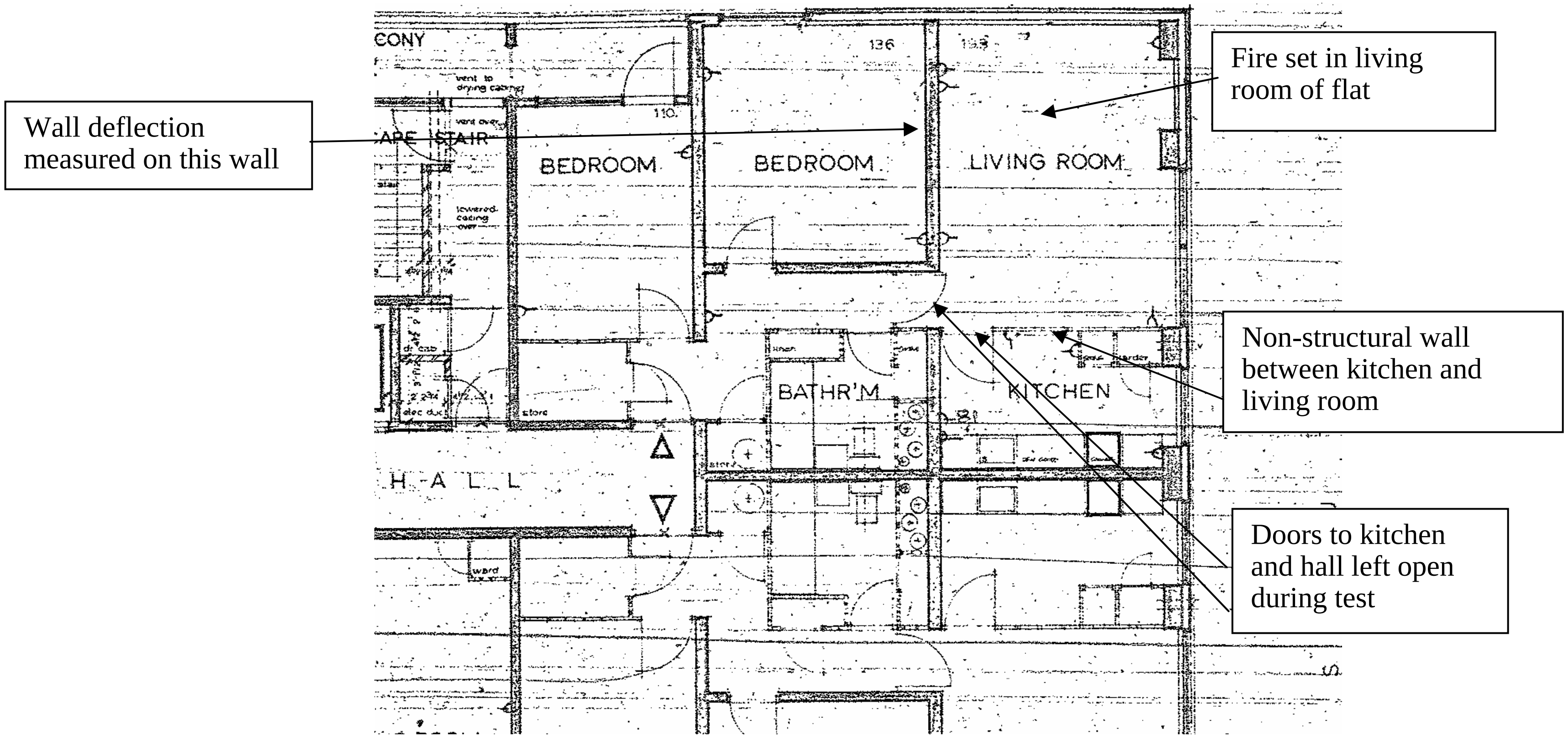

Figure 1. Extract from the Dalmarnock tower blueprints showing the layout of the flat in which the fire test took place.

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- the fire load was "real"; it resulted from office furniture being burnt rather than from burning wooden cribs or a gas furnace (see Chapters 2 & 3),
- both the fire and structural behaviour were monitored and well documented,
- the structure was a complete building rather than a structural element or set of elements,
- data relating to the fire behaviour and structural behaviour were recorded during both the heating and cooling phases of the fire.

The test has therefore provided both a valuable description of the behaviour of concrete structures in fire and also a unique set of data with which it will be possible to benchmark numerical modelling tools.

Instrumentation

Structural measurements taken during Test One consisted of deflections of the ceiling and one wall of the fire compartment; strains on the upper surface of the ceiling of the compartment and temperatures within the ceiling of the compartment.

Deflection measurements were taken with Linear Variable Displacement Transducers (LVDT) displacement transducers. To monitor the deflections of the ceiling of the fire compartment an array of 9 transducers were mounted on scaffold bars in the room above fire. The arrangement is shown in Fig. 2. Each deflection gauge was assigned a letter for ease of identification and its coordinates given by the *x-y* system indicated in the figure. The scaffold bars were supported on the edge of the floor slab and so the deflections recorded are changes relative to the edge of the slab; any overall change in the height of floor was not captured. The windows of this room were sealed to ensure that hot gases did not enter and affect the instrumentation. Using a similar method, horizontal deflections of the internal structural wall of the fire compartment were monitored by three transducers from a room adjacent to the fire (Fig. 1). As this room filled with hot gases in the later stages of the test, the recordings from these transducers are not entirely reliable; however, as shown below, the deflections appear negligibly small.

Slab temperature measurements were taken by means of thermocouples at six locations in the ceiling above the fire compartment. At each location temperatures were recorded at four depths in the slab. Details are given in Fig. 3 where each group of thermocouples are assigned a Greek letter for identification. The thermocouples were inserted into the slab by drilling an 18mm diameter hole through its entire depth, inserting the thermocouples and then filling the remaining space with cementitious grout. Care was taken to ensure that a small layer of grout was present between the lowest thermocouple and fire compartment so that the temperature measurements were those of the slab and not the hot gases. The locations of thermocouples within the depth of the slab are shown in the inset to Fig. 3.

Strain measurements were taken at 22 locations on the upper surface of the ceiling of the fire compartment as shown in Fig 4. Strains were recorded by electrical resistance strain gauges and the results later corrected for temperature variations using the manufacturer's correction curves. Temperatures were estimated from the nearest thermocouple to each of the strain gauges. The gauges were installed by smoothing a small area of concrete on the upper surface of the slab and gluing the gauges into position.

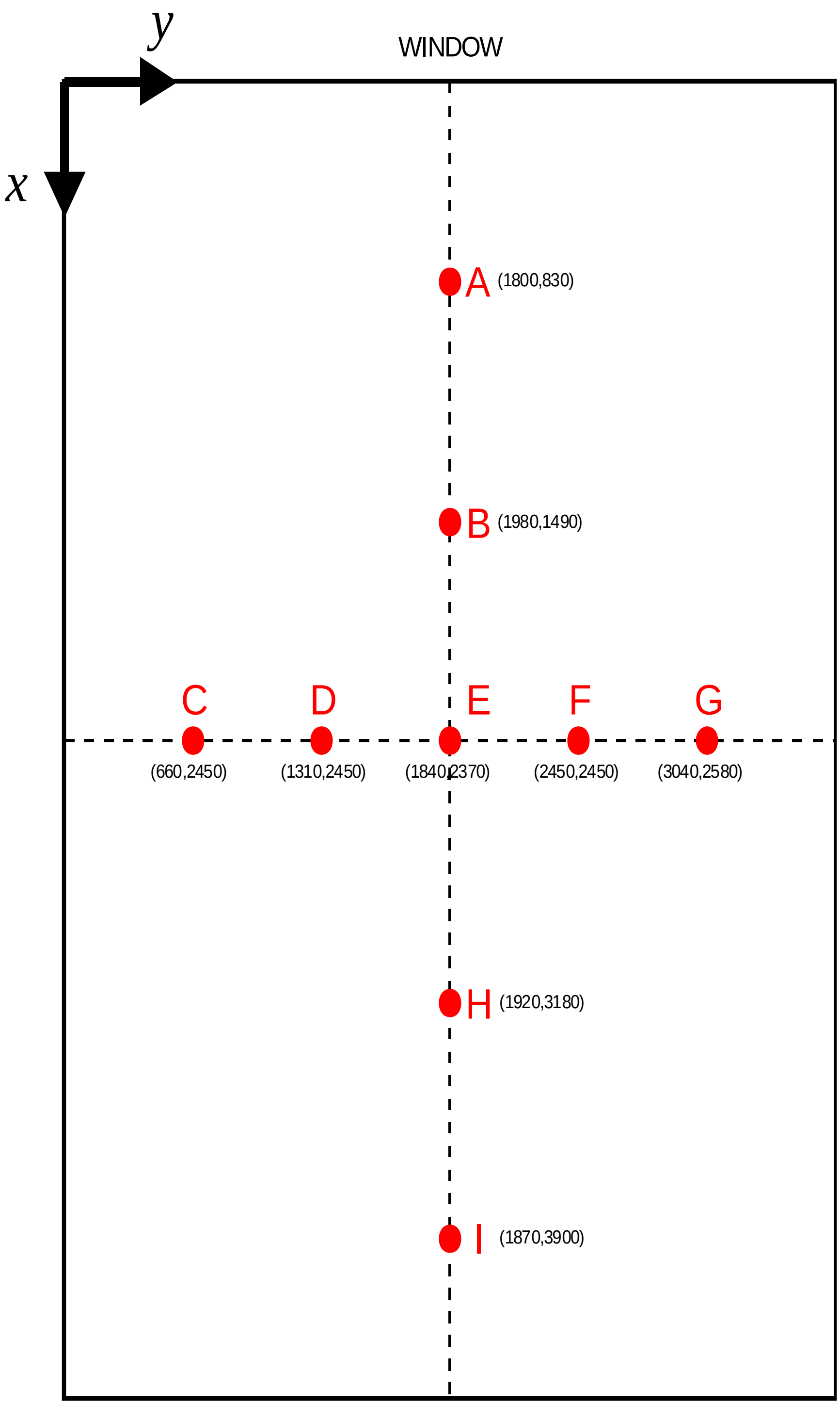

Figure 2. Locations of the deflection gauges on the upper surface of the heated concrete slab. Coordinates in mm.

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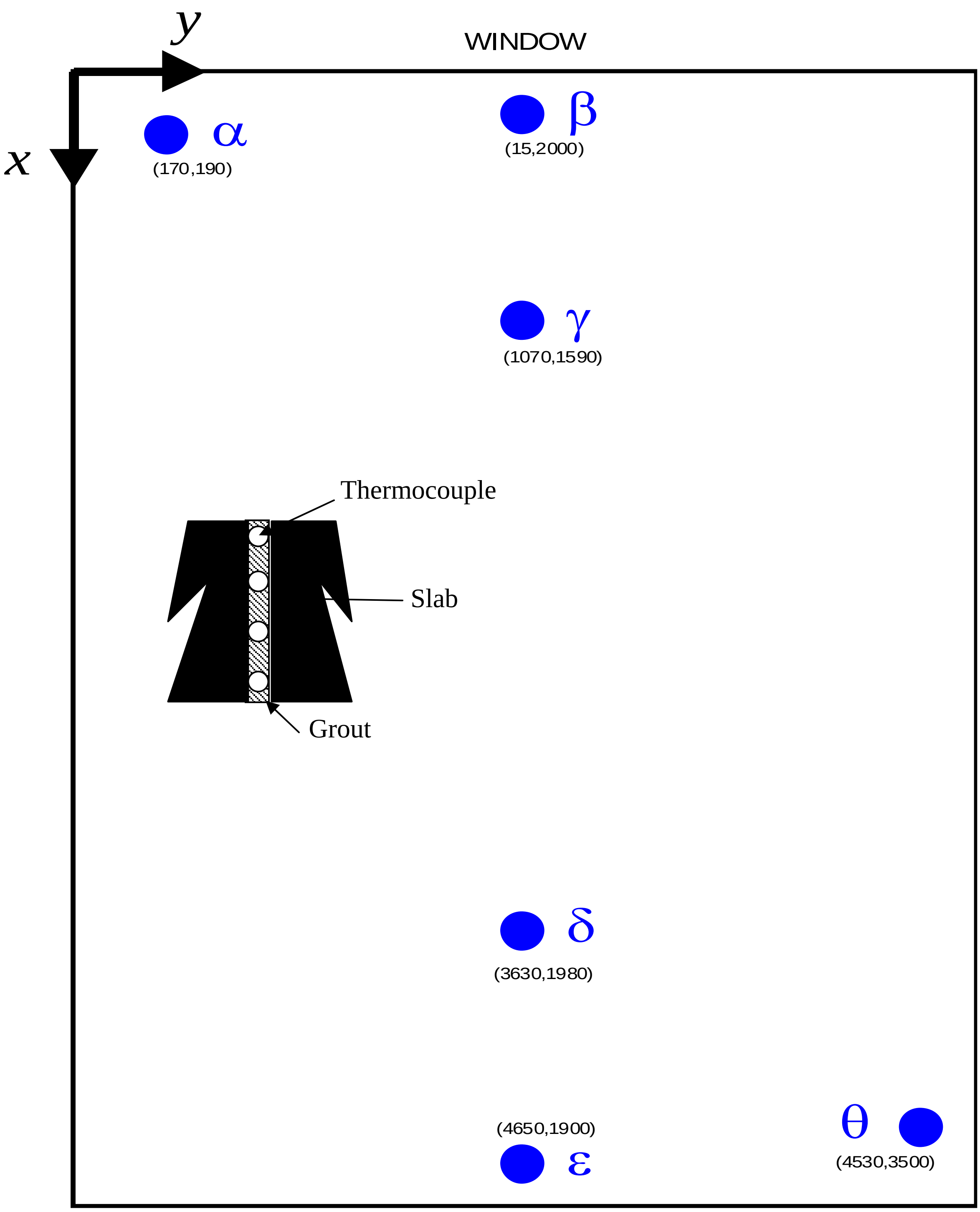

Figure 3. Locations of the thermocouples in the heated concrete slab. Coordinates in mm.

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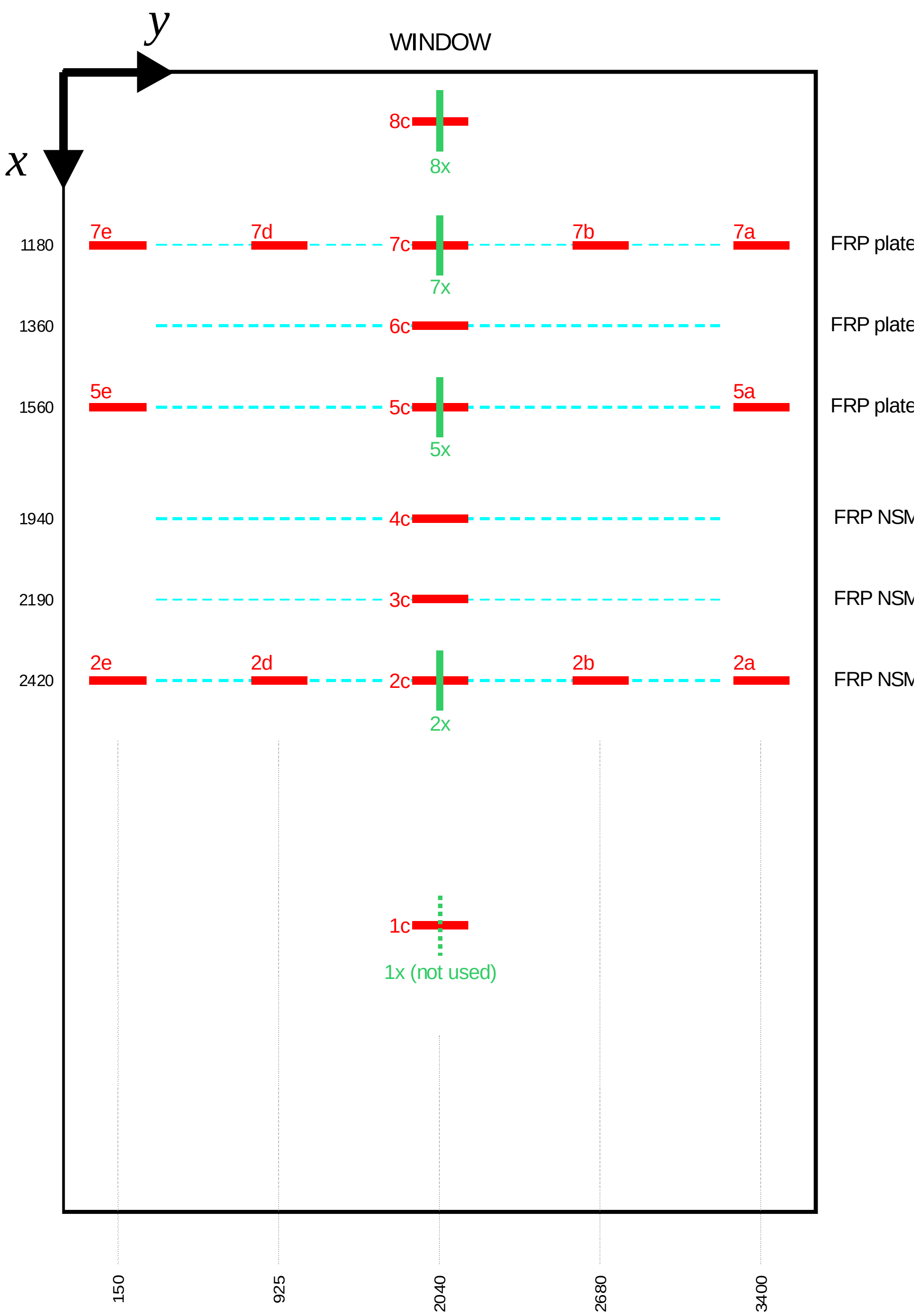

Figure 4. Locations of the strain gauges on the upper surface of the heated concrete slab. Coordinates in mm. The locations of boned FRP plates and bars are also shown.

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Results and Discussion

Thermocouple readings from within the ceiling slab are plotted in Fig. 5. The highest temperatures are recorded away from the window of the compartment at locations delta and epsilon. This occurred due to the ventilation to the fire initially being supplied via the doorway; it was only later in the fire that ventilation was available through the window of the compartment. The readings at location alpha are anomalous and it is suspected that this is due to a failure of instrumentation.

It is clear from Fig.5 that the locations at which highest temperatures occurred within the area of the slab were very localized. This is in marked contrast to the assumptions made in most design procedures. Temperatures in structural elements are typically based on estimates from either simple "natural fire" calculations or the results of zone models. Both these techniques assume the gases in a compartment fire are well mixed. While the results from this test show peak temperatures in the concrete that are comparable to those that would be predicted by standard techniques, the location of these peak temperatures are highly localized. This suggests that estimates of the energy absorbed by structures in fire are likely to be very conservative if based on standard techniques. It is therefore likely that most structures would exhibit significantly more robustness in fire than is currently predicted during design. Consequently, considerable savings in fire protection may be possible in performance-based design if methods of estimating structural temperatures are based on more advanced methods (such as numerical modelling) than are currently usual.

The high thermal capacity of concrete is illustrated by the manner in which the lower surface of the slab is heated much more rapidly and to higher temperatures than the internal part. It is also noticeable that the temperature of the lower surface of the slab dropped rapidly at all locations from around 1500s. This was due to fire-fighters spraying cold water on the slab when the fire was being extinguished. The internal portions of the slab maintained their temperatures despite fire fighting activities, indeed, the upper layers of the slab continued to get hotter even after the fire was completely extinguished.

The vertical deflections of the floor slab are shown in Fig. 6 where it can be seen that the peak deflection at the centre of the slab was around 10mm (span/deflection=360) and that 4mm of this deflection was recovered on cooling. Deflection gauges located towards each of the walls of the compartment recorded lower deflections in each case. It is notable that gauge C recorded negative (upward) deflections from around 1500s. It is believed that this resulted from a crack forming in the slab that effectively moved the support from the wall to slightly inside the fire compartment. The very small inward deflections recorded for horizontal deflections of the internal wall of the compartment (Fig. 7) suggest the heating of this wall was small in comparison with the compartment ceiling.

Strain gauge data is shown in Fig. 8. In general the curves indicate similar behaviour to the deflection readings with peak strains occurring just before fire-fighters entered the compartment. It is noticeable that some gauges suggest increasing strains during the cooling phase (e.g. gauges 7b and 1c). The reasons for this are not entirely clear,

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however, it may be due to local thermal expansion of some areas of the slab resulting in compression in other areas. This is one question that future numerical modelling of the test will aim to answer with certainty.

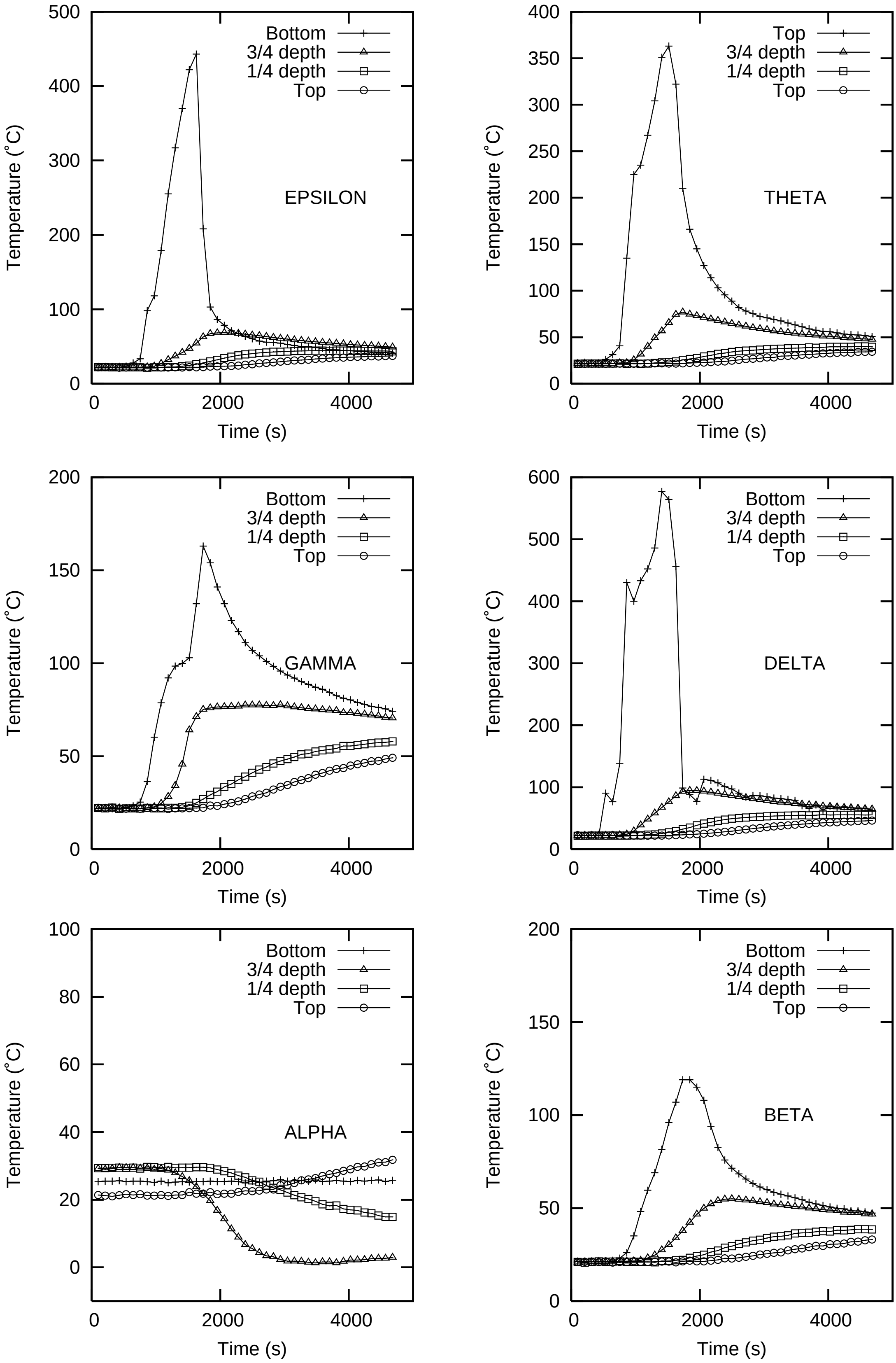

Figure 5. Temperature data recorded at the locations shown in Fig 3.

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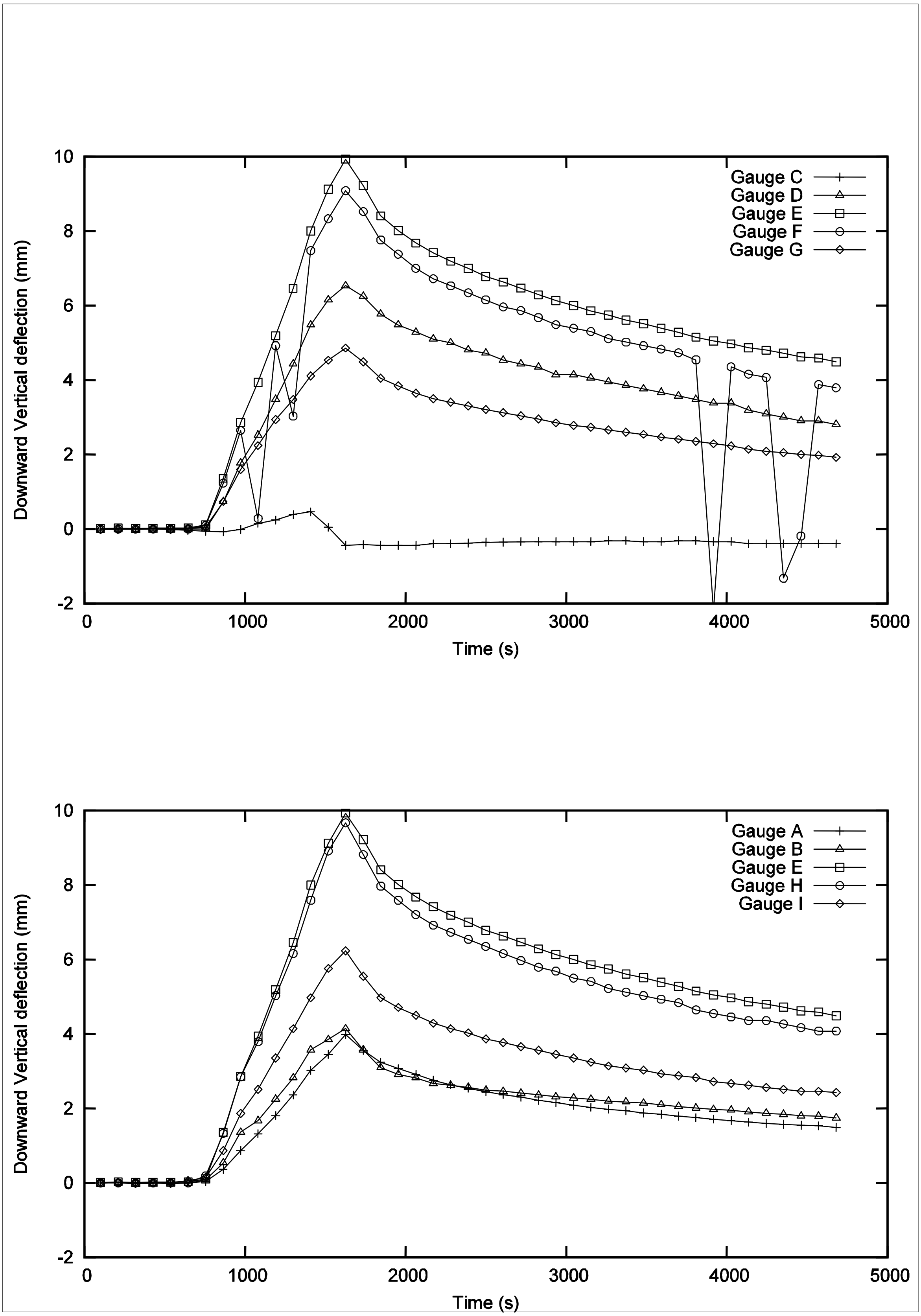

Figure 6. Vertical deflections of the heated floor slab from gauges placed at the locations indicated in Fig. 2.

After the test the structure was inspected. Despite fire-fighting operations, the fire compartment itself had almost entirely burnt out with little combustible material remaining. The lower (directly heated) surface of the ceiling was found to have shed all of the covering of plaster that was initially present, however, there was no spalling of any kind. This is of interest as the spalling behaviour of concrete in fire is the subject of considerable research effort at present (e.g. Hertz and Sorensen, 2005). In general it is found that fresh (wet) concrete and high strength concretes are more susceptible to spalling. Given that the concrete in the heated slab was dry (due to its age) and by modern standards of low strength, the lack of spalling in the test described provides anecdotal evidence to support these findings. However, the concrete was also initially covered in a layer of plaster which would have affected its heating rate and also have prevented direct impingement of flames in the early stages of the test. To date it appears the effects of these phenomena on concrete spalling behaviour have not been the subject of detailed study.

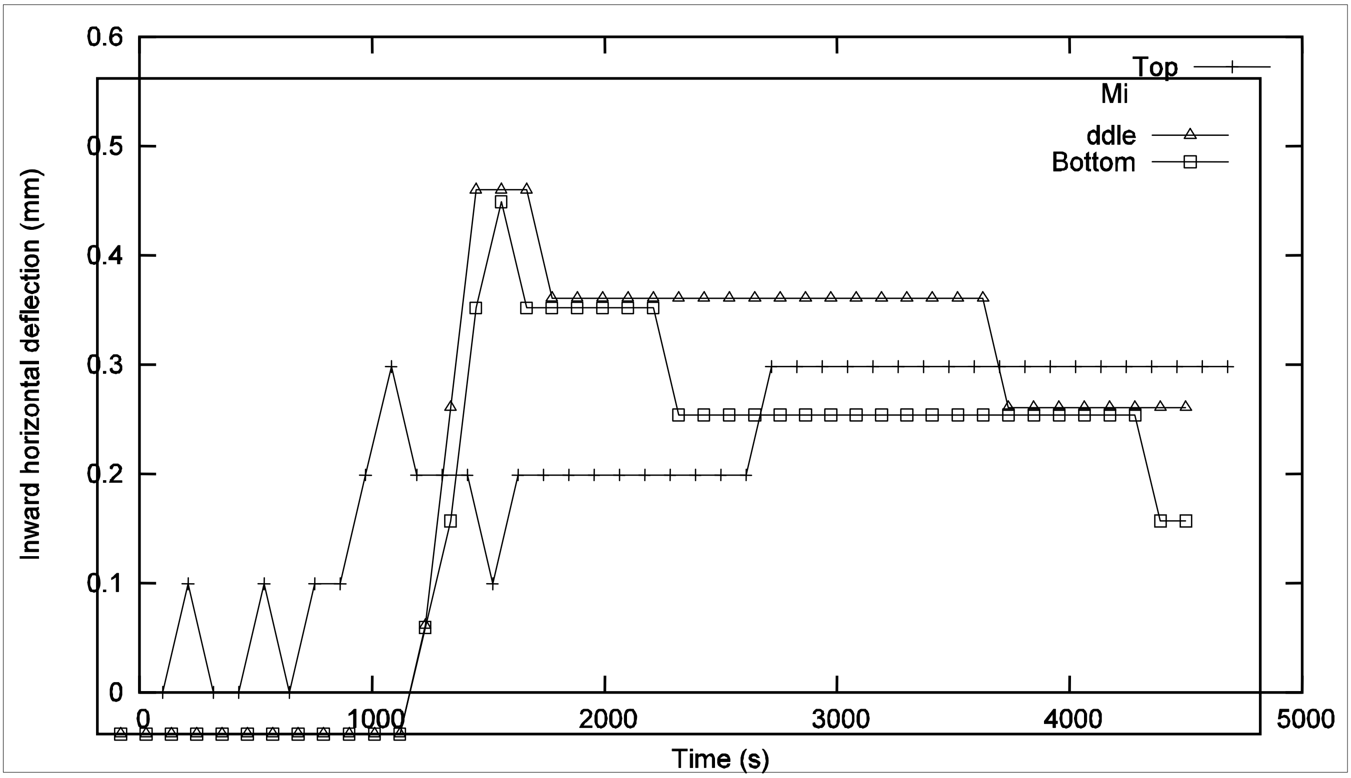

Figure 7. Horizontal deflections of the internal structural wall of the fire compartment.

The upper surface of the slab contained visible cracks which coincided with the locations at which the upper layer of slab reinforcement was curtailed. This is unsurprising as there would be a step change in the flexural stiffness of the slab in these locations. The fact that cracks did appear at these locations suggests that detailing of reinforcement may have implications for the behaviour of concrete structures in fire. Although no compartmentation failure occurred as a result of cracking in the test considered here, the chances of such a failure would be greater with the longer spans and thinner slabs that are present in many modern buildings. Since the cracks appeared at locations where the flexural stiffness of the slab changed abruptly due to reinforcement curtailment, it

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appears that specifying graduated reinforcement curtailment could reduce the chances of macro-cracks forming during a fire.

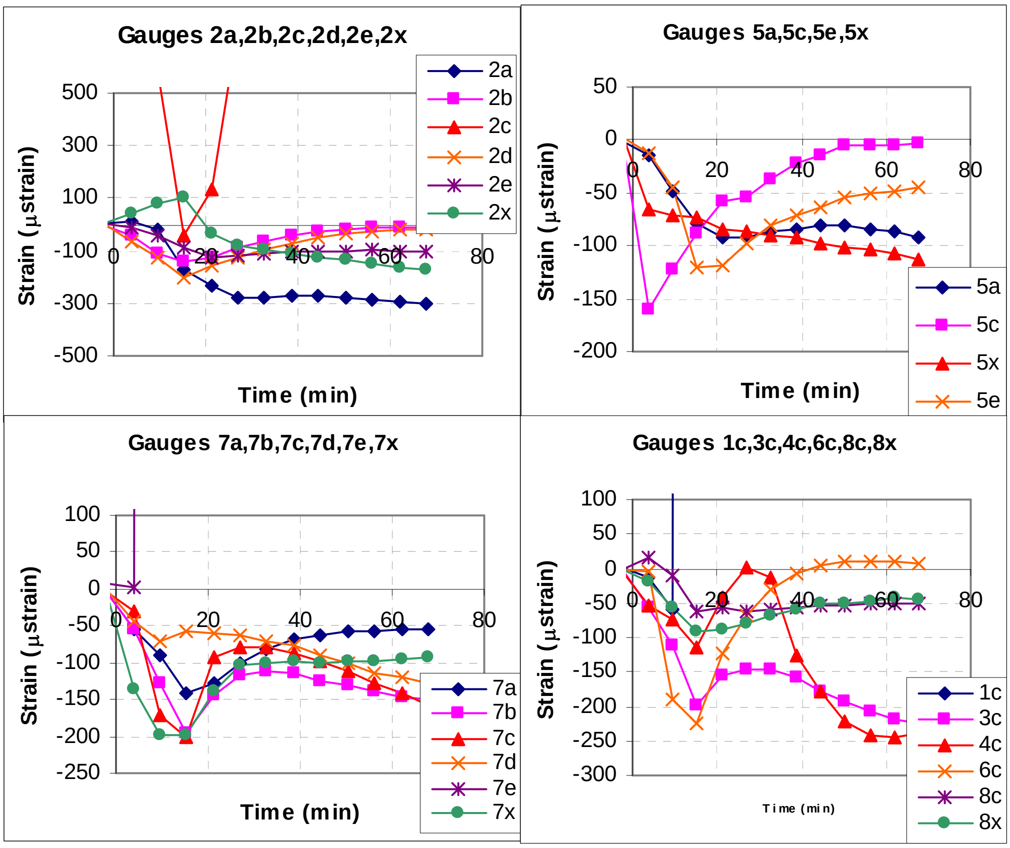

Figure 8. Strains on the upper surface of the heated slab at the locations indicated in Fig. 4.

Conclusions

A full-scale fire test has been conducted on a pre-existing, full-scale concrete structure. Observations from the test show that the structure performed well in fire with no structural or compartmentation failure. No spalling of concrete occurred. The set of data collected shows that the local nature of compartment fires results in highly non-homogenous heating of structures, a result at odds with assumptions usually made design practice. Results from the test are in a form that will allow benchmarking of both computer and analytical models of structural behaviour, heat transfer and material behaviour.

Acknowledgements

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